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Effect of Non-unity Power Factor Operation in Photovoltaic Inverters Employing Grid Support Functions

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Abstract

The high penetration of utility-interconnected photovoltaic systems is causing heightened concern over the effect that variable renewable generation will have on the electric power system (EPS). These concerns have initiated the need to amend the utility interconnection standard to allow functionalities, so-called *advanced inverter functions*, to minimize the negative impact these variable distributed energy resources may have on EPS voltage and frequency. Unfortunately, advanced functions, in particular volt-VAr, will result in non-unity power factor (PF) operation. The increased phase current results in additional conduction losses and switching losses in the inverter power electronics. These power losses have a direct impact on real power delivered to the grid at the point of common coupling (PCC) and an impact on inverter service life. This report provides analysis, simulation, and experimental evidence to investigate the effect of *advanced inverter functions* on non-unity PF operation.

REACTIVE POWER FUNCTIONS

A utility-interconnected PV inverter's normal operational mode is to convert all available energy from the dc source into kW in the most efficient and effective manner. Thus, maximum power point tracking (MPPT) is the standard mode of operation. The objective is economically motivated; PV system owners are compensated for kWh delivered to the grid, and the system investment has the best rate of return if it operates as intended. The recent desire for PV systems to produce anything other than real power is driven by system operator acknowledgement that a high level of PV system adoption can lead to power quality problems in the electric power system (EPS) if the penetration level for a given locality rises to a point where the distributed energy resources (DER) can influence the voltage of the local EPS.

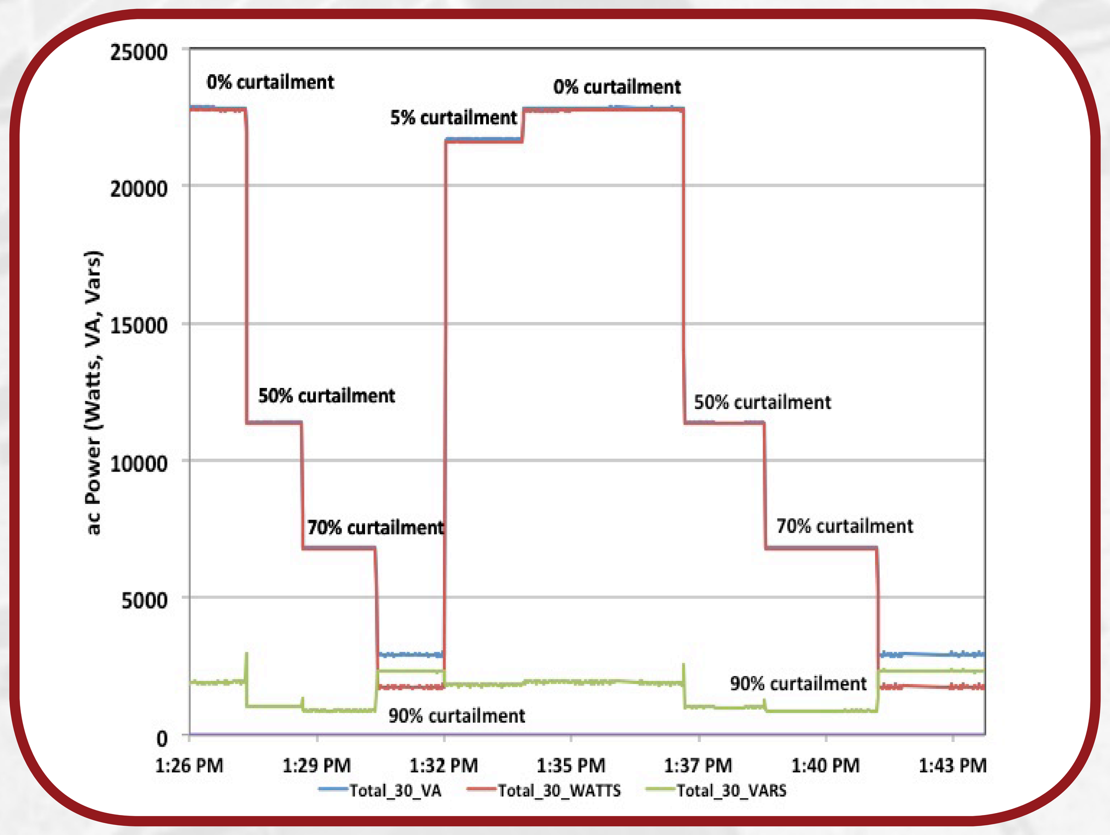
Results of Adjust Maximum Generation Level (INV2)

The inverter's output power is controlled via Ethernet to Modbus communication commands, and the intent of these evaluations is to assess how accurately the inverter tracks the command. The INV2 function sets the real power generation as a percentage of real power rated capacity.

For these tests, the dc source to the inverter is capable of delivering up to 120% of EUT rated output power and is held constant, regardless the commanded power level. This is to ensure the output is not curtailed other than by the communicated request. This test is not intended to address this function's optional ramp-time parameter, which defines the time the EUT moves from the current operational value to a new percentage of rated capacity.

The following test results show the inverter responding to communicated power level commands and the data recorded is used to determine the accuracy of the inverter to deliver the requested percentage of rated real power. The figure below shows the inverter responding to the power curtailment command. The table below shows the accuracy of the inverter's ability to deliver the commanded real power.

Inverter response to commanded real power



Commanded real power accuracy

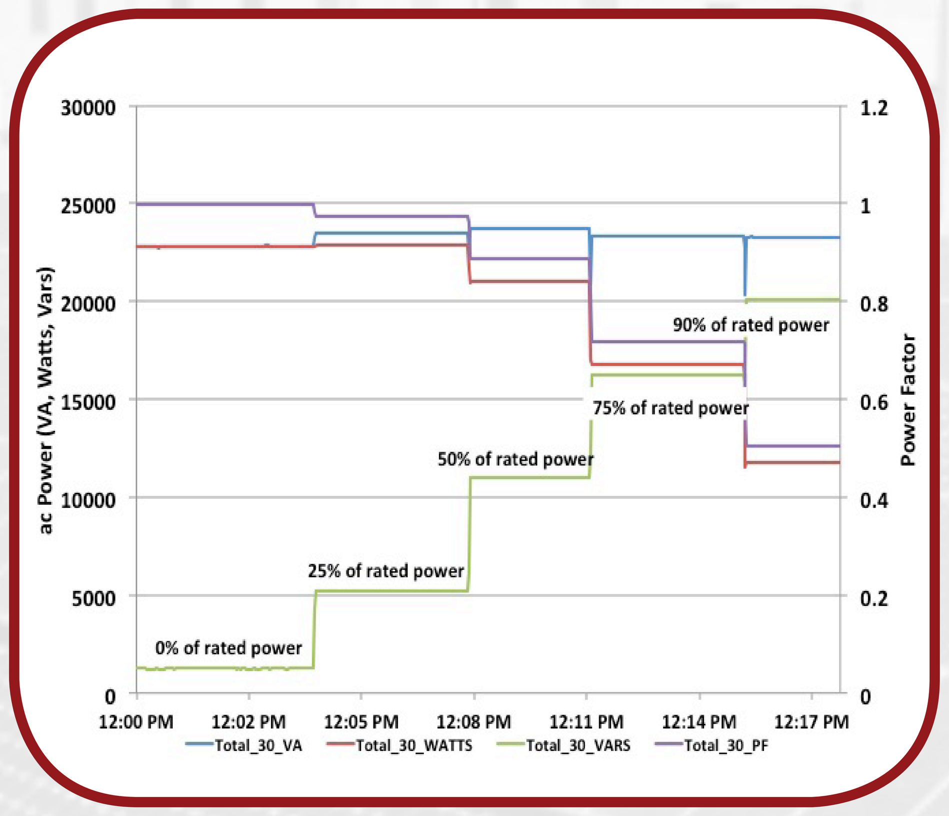
Power Curtailment	Expected power (W)	Power level (W)	% error
0%	22782	22782	0.00
50%	11391	11328	0.56
70%	6835	6759	1.11

Results of Adjust Power Factor (INV3)

The inverter' PF, i.e., displacement PF, is also set through communication commands. The advanced inverter function used is a VAr priority function (VV12), under which the requested reactive power is delivered regardless of real power curtailment (VAr priority). For these tests, the dc source to the inverter is capable of delivering up to 120% of EUT rated output power and is held constant, regardless the commanded power level and the inverter is delivering 100% of rated real power.

The EUT produces reactive power as a percentage of real power rating and the following test results show the inverter responding to reactive power commands to the inverter. The data presented in the figure below displays the responsiveness of the inverter and the table below shows the accuracy of the inverter's ability to deliver the commanded reactive power. For all reactive power commands over 25%, the inverter's kVA limits required it to reduce its real power output below 100%.

Inverter response to commanded reactive power



Command reactive power accuracy

% of rated	Expected VAr	measured VAr	% error	PF
25	5688.6	5231.8	8.0	0.97
50	11377.6	10967.0	3.6	0.89
75	17067.2	16267.3	4.7	0.72
90	20481.7	20092.1	1.9	0.51

Power Loss Calculations and Interpolation

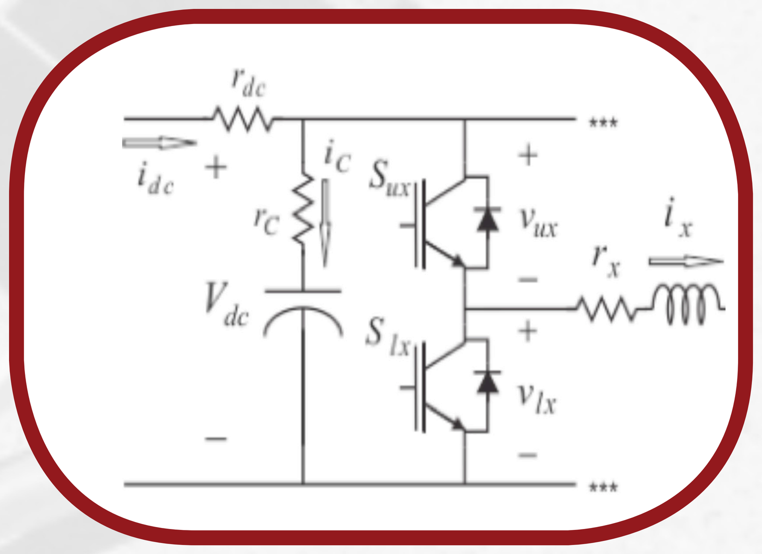
If the real power output is taken to be constant (i.e., not curtailed), then an inverter operating off of unity power factor will have a lower efficiency than one operating at unity power factor. The reason is because for non-unity power factor operation, the inverter must supply a higher current, and most of the key loss mechanisms in an inverter are dependent on current. For conductors (Equation (1)), dc bus (Equation (2)), and dc link capacitors (Equation (3)), the losses are the usual ohmic losses:

$$P_{filt,loss} = r_x i_x^2 \quad (1)$$

$$P_{dcbus,loss} = r_{dc} i_{dc}^2 \quad (2)$$

$$P_{C,loss} = r_C i_C^2 \quad (3)$$

Schematic showing typical inverter phase leg



where may represent phase currents i_a, i_b or i_c, r_x is the phase circuit resistance in Ohms, r_{dc} is the dc bus conductor resistance in Ohms and r_C is the dc link capacitor equivalent series resistance in Ohms. The semiconductor switches in the inverter will exhibit steady-state (ohmic) and switching losses. The ohmic losses depend on the square of the current in the usual way, but it can be shown that the switching losses depend on current as well.

There are two other important loss mechanisms that increase in inverters when operated at non-unity power factor: additional current flowing through the inverter's antiparallel diodes, which typically have higher losses than the main switches, and higher ripple curents through parasitic series resistances in dc filter elements.

If one were to model each loss mechanism and sum the losses, it should be possible to attain an accurate result. However, given the difficulty in accounting for each mechanism, it is convenient to consider the development of an empirical model, similar to what was done in the equation below at the device level, except the model would be applied to a whole inverter. As an example, an empirically derived loss model was developed for a single experiment. Specifically, a 25 kVA three-phase inverter was supplied by a PV emulator and evaluated at several PF levels. The inverter was allowed first to 'warm up' and then operated with a variable irradiance profile and PF levels of 0.5, 0.72, 0.87 and 0.97. The dc voltage was allowed to vary about a mean value of about 350 Vdc. The data was then fit to the following expression

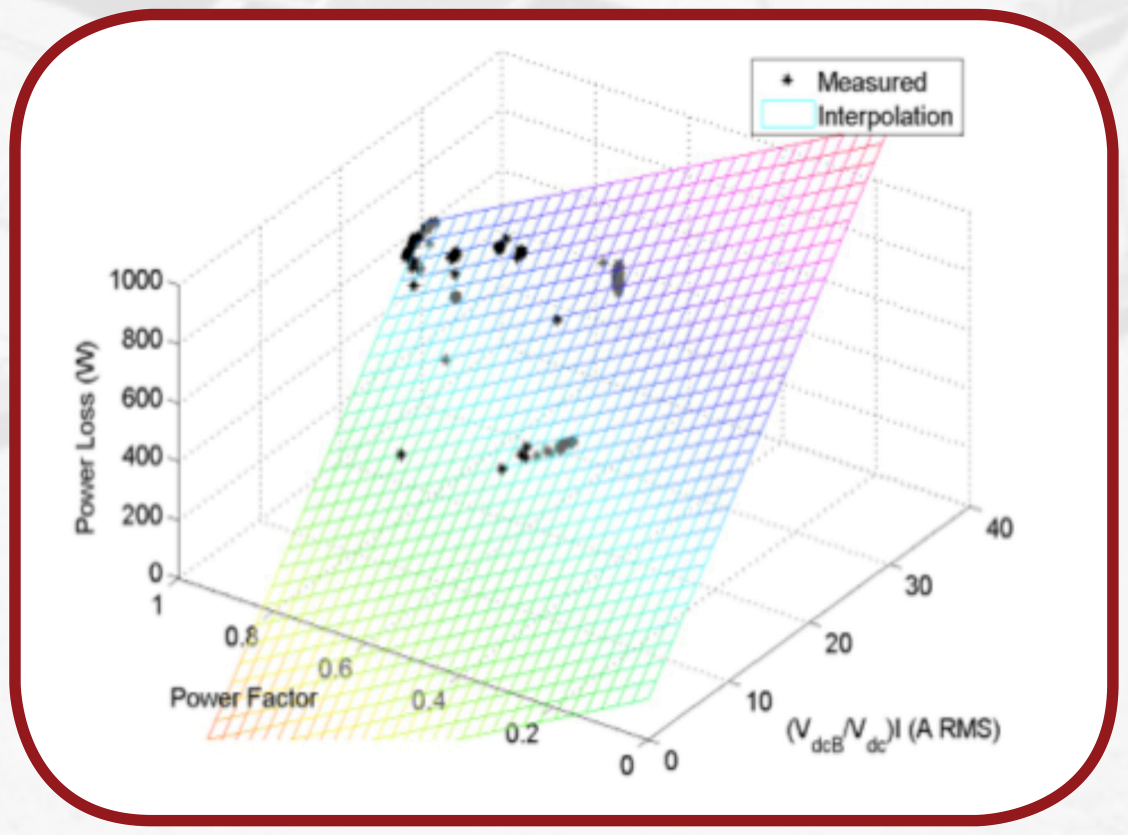
$$P_{loss} = K_I I_{RMS}\left(\frac{V_{dcB}}{V_{dc}}\right) + K_{PF} PF + K_b$$

Values used for Interpolation

Parameter	Value
K_i	45.28 V
K_{pf}	-883.3 W
K_h	137.9 W
K_{dcR}	350 Vdc

where P_{loss} is the power loss in Watts for the entire inverter, K_i is a interpolation term in Volts (i.e. Watts/Amp), I_{RMS} is the average RMS phase current of the three phases, V_{dcB} is the 'base dc link voltage' in Volts, K_{PF} is an interpolation term in Watts and K_b is a bias term in Watts. The expression was determined through trial and error and is not expected to be unique. Using over 1000 data points, a nonlinear least squares method was applied to determine the interpolation and bias values used in the equation above. These values are given in the table above. The data points were then compared to the values attained through interpolation. The result was a good fit to the data with a mean error of just 5.35%. The comparison is also plotted in the figure below.

Comparison of power loss data to empirical model



Conclusions

In this paper, non-unity PF advanced inverter functions were identified and the effects these advanced inverter functions have on the performance of the inverter and the ability for hardware to meet the programmed real and reactive power levels were assessed. Results demonstrated that non-unity PF decreases conversion efficiency. Several loss mechanisms were discussed and the complexity of summing the different loss mechanisms was noted. As an alternative, a method for interpolating inverter loss was presented with results from one experiment. The interpolation approach is empirical but the resulting expression is simple to apply and yields accurate results.

Exceptional service in the national interest

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